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ENHANCEMENT OF GROUP 3 AND GROUP 4 FACSIMILE STANDARDS TO INCLUDE COLOR

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With the advent of low-cost color scanners and printers, color facsimile is fast becoming a reality. Some color facsimile equipments are already appearing on the marketplace. At present there are no standards available from the CCITT or other standards groups that might ensure the interoperability of different manufacturers' equipments. The selection of a color space is possibly one of the most important decisions for color facsimile. Most importantly, the chosen color space should be "device independent" to allow accurate color reproduction and evaluation.

The objectives of this report are to evaluate candidate color spaces, to determine modification needed to include in Group 3 and Group 4 facsimile, and to investigate methods for regenerating continuous-tone images from halftones.

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NCS TECHNICAL INFORMATION BULLETIN 92-19

ENHANCEMENT OF GROUP 3 AND GROUP 4 FACSIMILE STANDARDS TO INCLUDE COLOR

NOVEMBER 1992

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FOREWORD

Among the responsibilities assigned to the Office of the Manager, National Communications System, is the management of the Federal Telecommunication Standards Program. Under this program, the NCS, with the assistance of the Federal Telecommunication Standards Committee identifies, develops, and coordinates proposed Federal Standards which either contribute to the interoperability of functionally similar Federal telecommunication systems or to the achievement of a compatible and efficient interface between computer and telecommunication systems. In developing and coordinating these standards, a considerable amount of effort is expended in initiating and pursuing joint standards development efforts with appropriate technical committees of the International Organization for Standardization, and the International Telegraph and Telephone Consultative Committee of the International Telecommunication Union. This Technical Information Bulletin presents and overview of an effort which is contributing to the development of compatible Federal, national, and international standards in the area of facsimile. It has been prepared to inform interested Federal activities of the progress of these efforts. Any comments, inputs or statements of requirements which could assist in the advancement of this work are welcome and should be addressed to:

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ENHANCEMENT OF
GROUP 3 AND GROUP 4 FACSIMILE
STANDARDS TO INCLUDE COLOR

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1.0 INTRODUCTION

This document summarizes work performed by Delta Information Systems, Inc. for the Office of Technology and Standards of the National Communications System, an organization of the U. S. government. The effort was specified by Task 1, Subtask 5 of contract number DCA100-91-C-0031.

1.1 Background

With the advent of low-cost color scanners and printers, color facsimile is fast becoming a reality. Some color facsimile equipments are already appearing on the marketplace. At present there are no standards available from the CCITT or other standards groups that might ensure the interoperability of different manufacturers' equipments. The selection of a color space is possibly one of the most important decisions for color facsimile. Most importantly, the chosen color space should be "device independent" to allow accurate color reproduction and evaluation.

1.2 Objectives

The objectives of this report are

- to evaluate candidate color spaces,
- to determine modifications needed to include color in Group 3 and Group 4 facsimile, and
- to investigate methods for regenerating continuous-tone images from halftones.

1.3 Report Organization

This report has seven sections:

1.0 Introduction
2.0 Color Space Comparison
3.0 Compressing Color
4.0 Enhancing Group 3 and Group 4 Facsimile to Include Color
5.0 Regenerating Images from Halftones
6.0 Conclusions, Recommendations, and Items for Future Study

Section 1.0, "Introduction," provides background information and discusses this reports organization.

Section 2.0, "Color Space Comparison," discusses candidate color spaces.

Section 3.0, "Compressing Color," discusses compression techniques applicable to the candidate color spaces.

Section 4.0, "Enhancing Group 3 and Group 4 Facsimile to Include Color," discusses how Group 3 and Group 4 facsimile could be enhanced to include color.

Section 5.0, "Regenerating Images from Halftones," discusses the reconstruction of output images from halftone inputs.

Section 6.0, "Conclusions, Recommendations and Items for Future Study," summarizes conclusions and recommendations for adding color to fax and suggests additional investigations.

2.0 COLOR SPACE COMPARISON

In general, fax color scanners scan documents using Red, Green, and Blue light (RGB); while fax color printers print facsimiles using Cyan, Magenta, and Yellow inks (CMY). These two color spaces represent different color mixing laws with opposing characteristics. RGB represents the additive color mixture law and is used primarily in television, CRT's, etc.; whereas CMY represents the subtractive color mixture law and is used primarily in printing, painting, etc. Mixing together equal amounts of red, green, and blue light produces the color white; mixing together equal amounts of cyan, magenta, and yellow inks produces no color or black.

Making an accurate color facsimile usually requires carefully transforming from the input device's RGB to the output device's CMY color space. This transformation must account for each device's reference light source (or illuminant) if color accuracy is to be maintained.

A color space for facsimile must consider

- Color stability,
- Image quality,
- Color space transformations,
- Compatibility with monochrome,
- Compatibility with existing standards, and
- Device independence.

2.1 Color Spaces

Six candidate color spaces for representing color were considered for facsimile:[1],[2],[3],[4]

- Red, green, and blue (RGB),
- Cyan, magenta, and yellow (CMY),

- YCrCb,
- CIEXYZ,
- CIELUV, and
- CIELAB.

All of the candidates are capable of representing all visible colors.

2.1.1 RGB Color Space

The RGB color space uses Red, Green, and Blue colored lights to represent the color gamut. Producing a particular color within that gamut is accomplished by mixing together three lights in specific intensities.

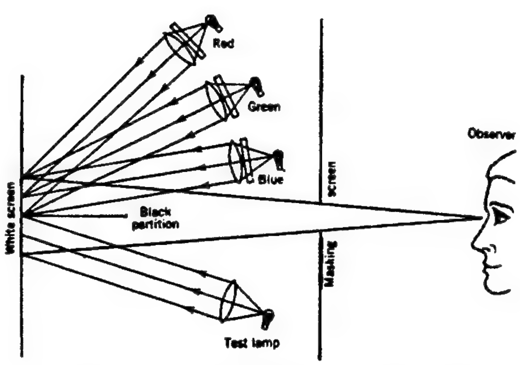

Figure 2-1. Color Matching Experiment

The RGB color space is a result of research conducted prior to 1931. At that time, several researchers were performing experiments in color matching. They had observers view a white screen illuminated by four lamps (See Figure 2-1). One lamp was designated as the test lamp and it illuminated one side of the screen. The other side of the screen was illuminated by the remaining three lamps (primaries). By varying the intensities of the primaries the observers would try to match the test color. Most, but not all colors could be matched this way. However, by mixing some of the primaries' light with the test color a match could be made with all. Adding primaries' light to the test color is considered a subtraction from the primaries on the other side of the screen. Thus, theoretically, all the colors of the spectrum could be matched by mixing positive and "negative" amounts of the three primaries. The primaries chosen were red, green, and blue. Figure 2-2 shows the relative amounts needed by a

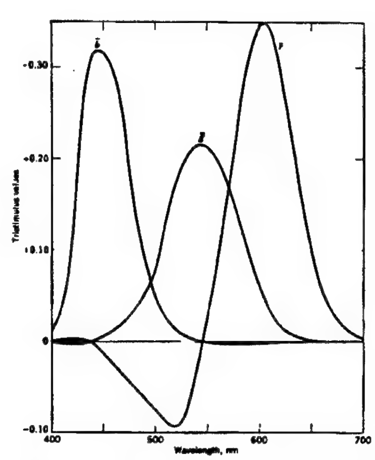
Figure 2-2. RGB Color Space

person with normal color vision to match any of the other spectrum colors, provided each of the spectrum lights emits the same amount of power. By knowing the intensities of the primaries (tristimulus values) any color can be defined in terms of the RGB color space.

2.1.2 CMY Color Space

The complement of the RGB color space is the CMY color space. The CMY color space obeys the subtractive color mixture laws and generally applies to paints, inks, pigments, etc. Its primary colors are Cyan, Magenta, and Yellow, the respective complements of red, green, and blue. Because this space obeys the subtractive color mixture laws, when cyan, magenta, and yellow are mixed in equal amounts the color black should be produced. However, in practice getting a true black is difficult. To correct this, black is sometimes added as a "fourth" primary.

2.1.3 XYZ Color Space

During 1931, it was decided to eliminate the negative numbers among the RGB tristimulus values. This was done mainly for computational reasons, but also because the sign change made it more difficult to develop direct-reading photoelectric colorimeters. So, a mathematical transformation of the RGB color space to a new color space was made. This new color space, the XYZ color space, cannot be produced by any real lamps (See Figure 2-3). However it does have advantages. The spectrum locus and its purple line are completely enclosed by the triangle formed by the chromaticity points of X, Y, Z (See Figure 2-4). This means that the tristimulus values of any real color are never negative. Secondly, the Y tristimulus values are identical to the standard observer's spectral response curve. This means that only the Y tristimulus value contributes luminance to a color. The other two tristimulus

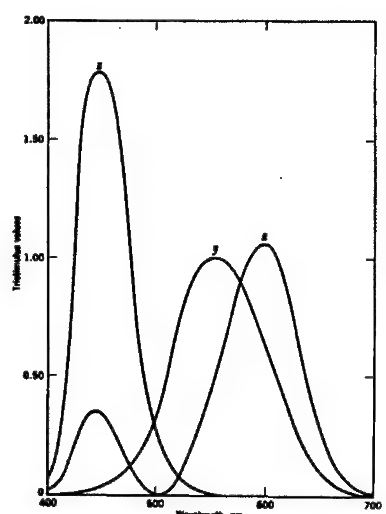

Figure 2-3. CIE 1931 (X, Y, Z) Standard Colorimetric System

values, X and Z, provide a color's chromaticity with no luminance. The XYZ color space is known as the "CIE 1931 (X, Y, Z) Primary System of Color Specification."

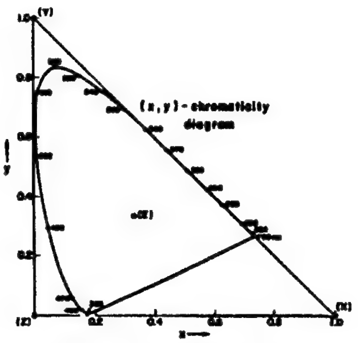

Figure 2-4. Chromaticity Diagram

2.1.4 CIELAB Color Space

The CIELAB color space is a mathematical model of the visual processes that govern color discrimination in order to predict perceived colors. This model uses a measure of distance in a postulated space to predict the magnitude of perceived color differences. Colors within the postulated space are represented by points or vectors and the distance between them determine the difference in perceived color. In general, the CIELAB color space is used with subtractive color processes such as paints, inks, etc.

CIELAB is an abbreviation for the CIE L* a* b* color space. It is an approximately uniform opponent-type space and is a nonlinear transformation of the CIE X, Y, Z color space (See Figure 2-5).[1] The CIELAB color space assumes that a color cannot be red and green at the same time, or yellow and blue at the same time, though it can be both red and yellow as in oranges, or red and blue as in purples, and so on. Therefore redness or greenness can be expressed as a single number (a*) which is positive for red colors and negative for green colors. Similarly, yellowness or blueness can be expressed as a single number (b*), which is positive for yellow colors and negative for blue colors. The third term "L*" describes the lightness of the color.

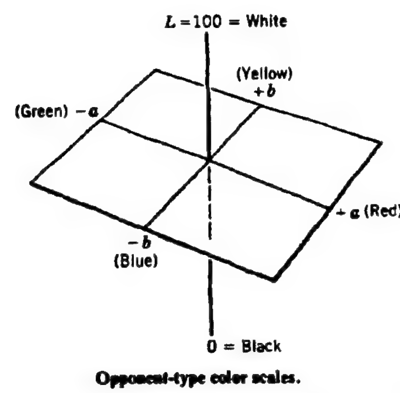

Figure 2-5. Opponent-Type System

[1] In the XYZ space the proximity of tristimulus values have little bearing on the similarity of perceived colors. Both the CIELAB and CIELUV color spaces are attempts to correct this.

2.1.5 CIELUV Color Space

The CIELUV color space is a linear transformation of the CIE X, Y, Z color space. A linear transformation preserves additive color mixing features. These features are important for color television and graphic arts applications.

CIELUV is an abbreviation for the CIE L^* u^* v^* color space. It, like CIELAB, is an opponent-type color space. L^* is again the lightness of the color with u^* as the red-green coordinate (red positive, green negative) and v^* as the yellow-blue coordinate (yellow positive, blue negative). Neutral colors (when u^* and v^* are zero) are located on the L^* (neutral) axis with black, whose location is uncertain in the XYZ space, being where L^* is zero. CIELUV is useful, particularly to television, because in its associated chromaticity diagram, additive mixtures of stimuli lie on the straight line joining the component colors and the color center of gravity law can be applied.[2] This is not true of CIELAB, although either may be used to predict color differences. The perceptual uniformity for CIELUV is about equally as good (or bad) as CIELAB.

2.1.6 YCrCb Color Space

The YCrCb color space is an international standard for component video coding (CCIR 601). It is an attempt to produce a digital signal that is more compatible with National Television System Committee (NTSC), Phase Alternation Line (PAL), and Sequentiel Couleur avec Memoire (SECAM) color television systems. The luminance and chrominance components are linear combinations of gamma corrected $\tilde{R}$, $\tilde{G}$, $\tilde{B}$ normalized either to NTSC's reference white C or PAL's and SECAM's reference white D_{65}. All three components are quantized with 8 bits. The maximum and minimum values are reserved for synchronization, which leaves the range 1-254 available for video. Maximum and minimum values of Cr occur for red ($\tilde{R}=1$, $\tilde{G}=\tilde{B}=0$) and cyan ($\tilde{R}=0$, $\tilde{G}=\tilde{B}=1$), respectively. Maximum and minimum values of Cb occur for blue ($\tilde{R}=\tilde{G}=0$, $\tilde{B}=1$) and yellow ($\tilde{R}=\tilde{G}=1$, $\tilde{B}=0$), respectively.

---

2 The center of gravity law uses a ratio of the primaries present in the component colors to determine where the mixture of the two will be on the straight line joining them.

2.2 Color Stability

The perceived stability of a color is dependent on at least two factors: the color rendering mechanism (e.g., monitor or printer) and the eye's color-difference threshold.[5] For rendering mechanisms, the reference illuminant (i.e., white point) usually varies from device to device with corresponding shifts in other colors. For example, if the change in the white point is not considered, the white shown on a monitor is likely to appear as a bluish white when printed on paper.

In television, the NTSC signal specifications were designed so that equal signals would produce a display white of the chromaticity of illuminant C.[6] Illuminant C, with a color temperature of about 6800 K, is an approximation of average daylight from an overcast north sky at midsummer, a bluish white.[7] For many years most home receivers were set so that equal signals produced an even bluer white. This was to achieve satisfactorily high brightness and to avoid excessive red/green current ratios with available phosphors. With modern phosphors, high brightness and red/green current equality can be achieved for a white at the chromaticity of illuminant D_{65}. Since D_{65}, with a color temperature of 6500 K (natural daylight; less blue than illuminant C), is very close to illuminant C, the color rendition is generally better than with the bluer balance of older receivers.

Fluorescent lamps, often used in color scanners, have color temperatures in the range of 3,000 to 4,500 K. Their spectral power distributions do not approximate those of natural daylight or D_{65}.[8] (See Figure 2-6. (1) standard warm white; (2) white; (3) standard cool white; and (4) daylight. The distribution curves have been scaled to provide a common value of 100 at λ = 650 nm.) The large spectral differences can lead to unacceptable mismatches that are supposed to color match under daylight. Fluorescent lamps generally have less blue-greenness and more orange-reds than daylight. Images scanned using a fluorescent lamp as the illuminant and subsequently displayed on a monitor with a white close to D_{65} may need more blue-greens added. If the corrected image is printed without accounting for white point shifts, it's likely to have a bluish cast.

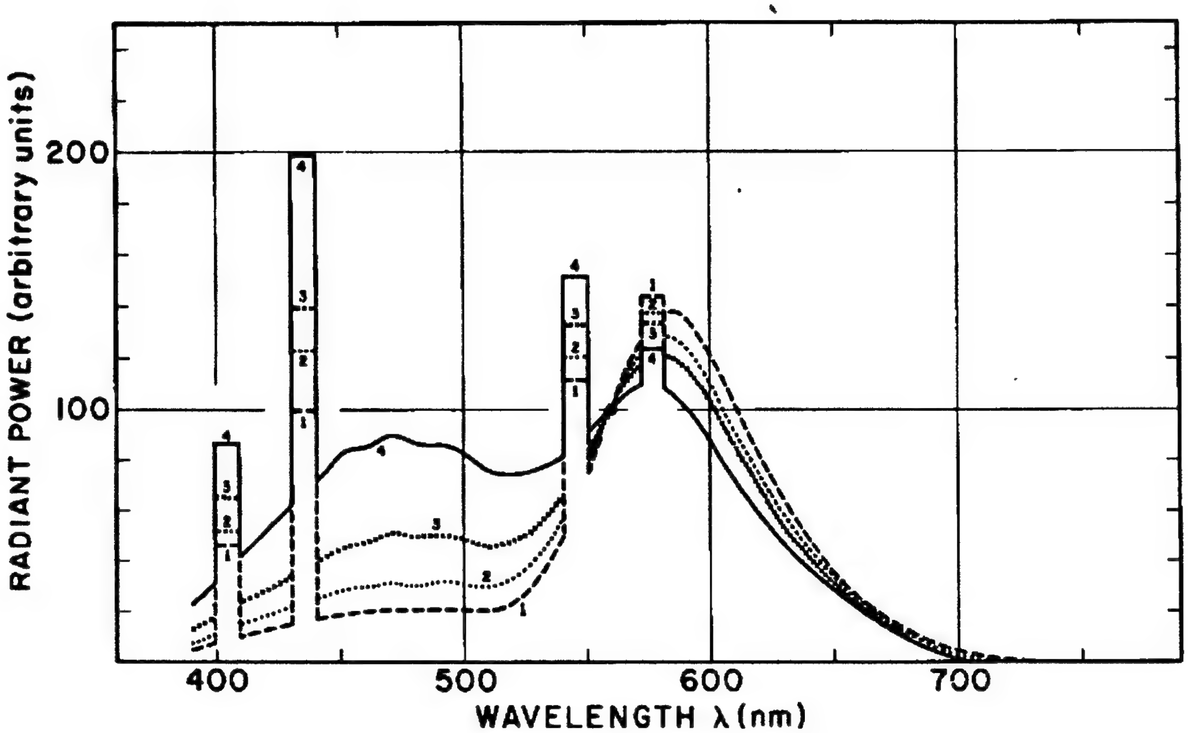

Figure 2-6. Relative spectral radiant power distributions of common fluorescent lamps.

The RGB, CMY, YCrCb and CIEXYZ color spaces have no formal mechanism to account for changes in white-points, while CIELAB and CIELUV do. (See Figure 2-7.) In addition, for some devices (like monitors) the white point can shift over time. Some causes of these shifts are device warming, changes in room ambient temperature, and age.

The eye's color-difference threshold is the point at which the human eye just detects a change in color. A white displayed on several monitors side-by-side may vary, but the variations will go undetected if the variations are below an observer's color-difference threshold.

The eye's color-difference threshold usually follows an elliptical contour around a color. Color-difference thresholds were measured by McAddam starting in 1942 and are known as McAddam ellipses. (See Figure 2-8.) Ellipses for observers usually vary from one observer to another and indicate an observer's color-difference perceptibility. Colors inside the ellipses are usually considered identical to the color at the ellipse's center, those outside are not.

CIELAB

For values of X/X_n, Y/Y_n, Z/Z_n greater than 0.01:

$$L^* = 116(Y/Y_n)^{1/3} - 16$$
$$a^* = 500[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}]$$
$$b^* = 200[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}]$$

For values of X/X_n, Y/Y_n, Z/Z_n less than 0.01:

$$L^* = 116[f(Y/Y_n) - 16/116]$$
$$a^* = 500[f(X/X_n) - f(Y/Y_n)]$$
$$b^* = 200[f(Y/Y_n) - f(Z/Z_n)]$$

where:

$f(Y/Y_n) = (Y/Y_n)^{1/3}$ for $Y/Y_n > 0.008856$

$f(Y/Y_n) = 7.787(Y/Y_n) + 16/116$ for $Y/Y_n \leq 0.008856$

$f(X/X_n)$ and $F(Z/Z_n)$ are similarly defined

X_n, Y_n, and Z_n are the tristimulus values of the white point

CIELUV

$$L^* = 116(Y/Y_n)^{1/3} - 16$$
$$u^* = 13L^*(u' - u'_n)$$
$$v^* = 13L^*(v' - v'_n)$$

where: u'_n and v'_n refer to the white point

Figure 2-7. Equations for the CIELAB and CIELUV Color Spaces

Unavoidable changes (e.g., due to temperature, age, etc.) in an input or output device's white point are likely to affect how colors are rendered. Nevertheless, as long as changes in color remain below an observer's color-difference perception level (some observers are more sensitive than others), the observer will be unable to detect the difference.

2.3 Image Quality

In theory, image quality is unaffected by all the color spaces. In practice, most input and output devices use only a limited gamut. For example, monitors are limited by the tristimulus values of their primaries (usually RGB), and printers are limited by the tristimulus values of their inks (usually CMY).[9],[10] (See Figure 2-9 and Figure 2-10.) These two gamuts overlap to a large extent. Nevertheless, there are areas where there is no overlap. (See Figure 2-11.) As a result, some colors that are reproducible on a monitor can not be printed, and vice

versa. Most natural colors are pastel and occur near the center of the triangles. (See Figure 2-12.)

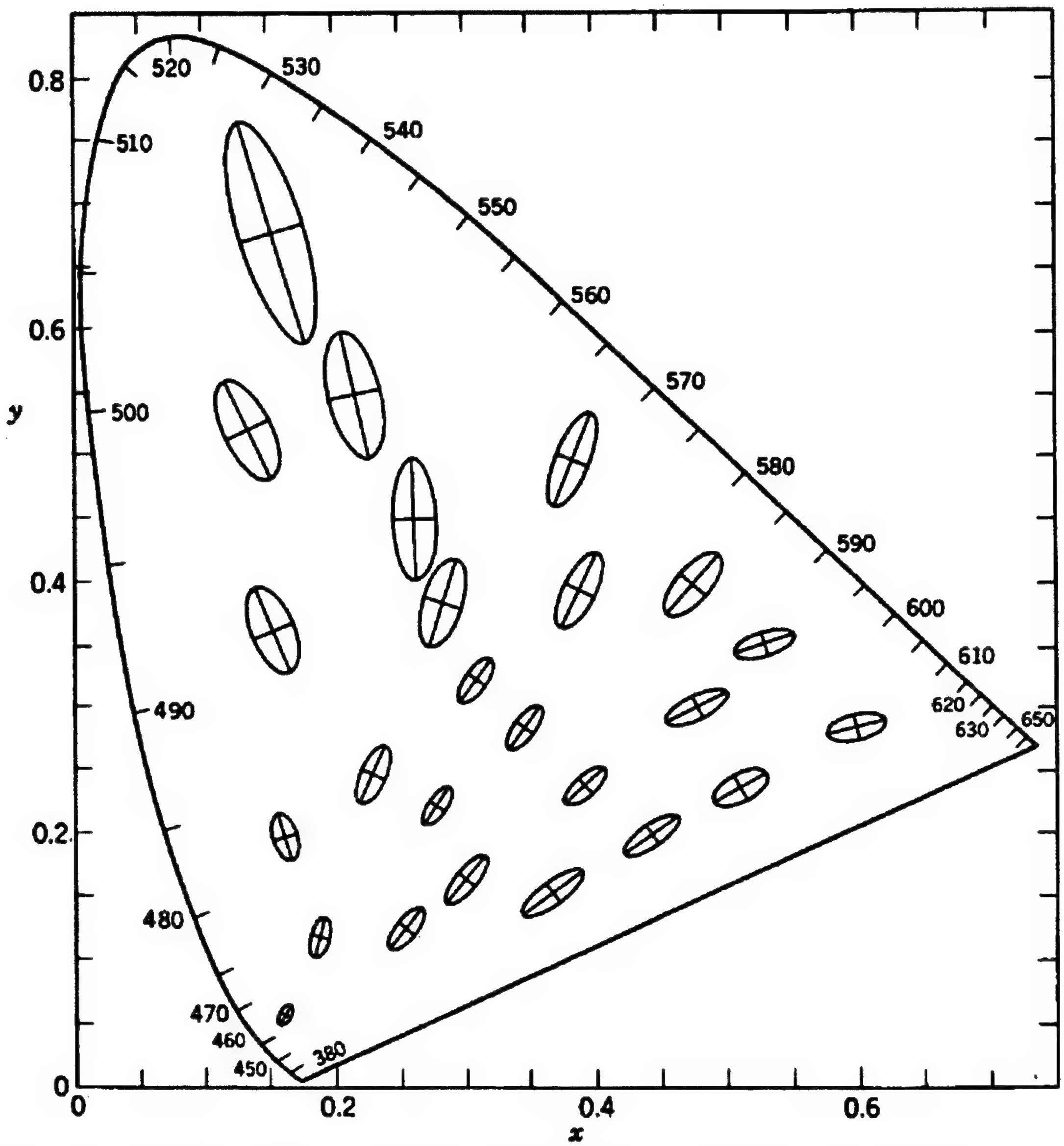

Figure 2-8. McAddam Ellipses. The axes of the ellipses are 10 times their actual lengths.

2.4 Color Space Transformations

Most color input and output devices inherently use a particular color space. Scanners usually use RGB, and printers usually use CMY. As a result, a

transformation from the RGB to the CMY must usually occur. The simplest approach is to convert directly from RGB to CMY when a scanned image is printed.

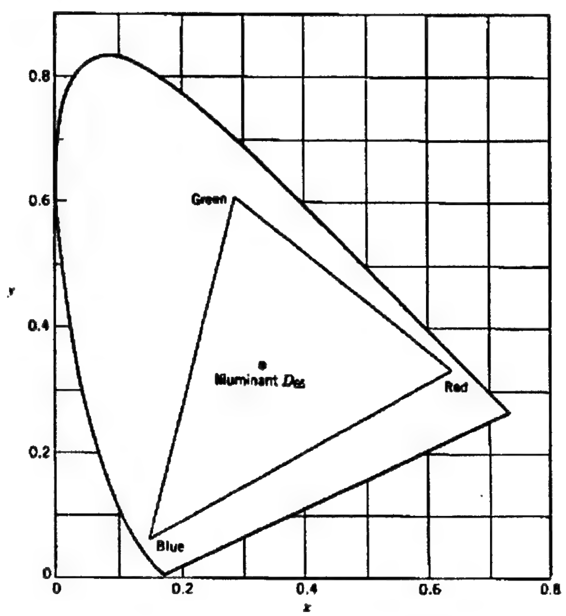

Figure 2-9. Gamut using Television RGB Phosphors

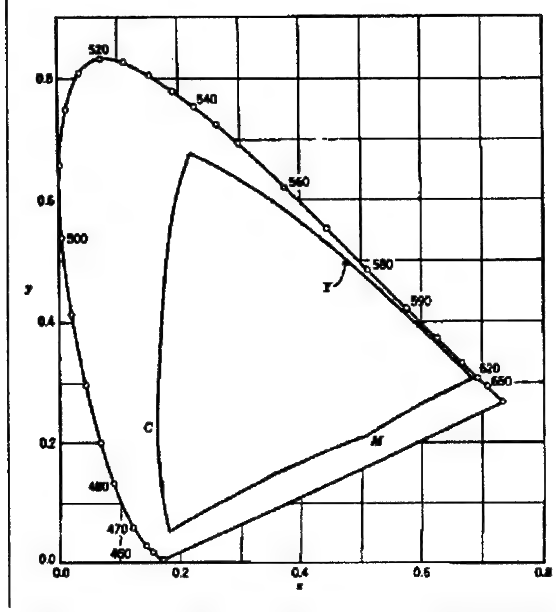

Figure 2-10. Gamut using a Color Photographic Process's Dyes

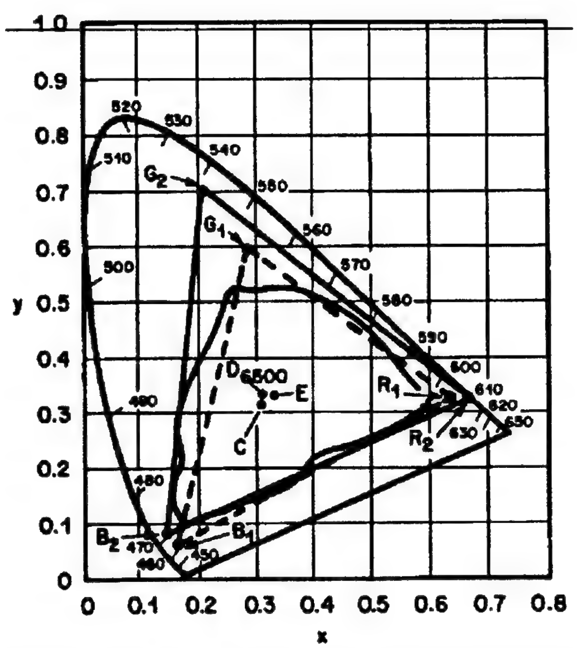

Figure 2-11. PAL Gamut(1), NTSC Gamut(2), and Gamut of Ink, Pigments, and Dyes (Irregular Curve)

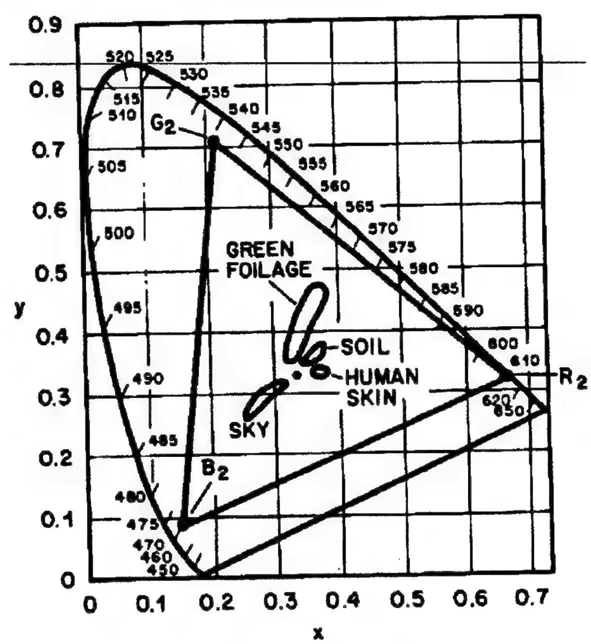

Figure 2-12. Natural Colors Gamut

This approach, however, does not account for changes in white points from one device to another. As a result, the output image is unlikely to be an accurate

rendition of the original. Transformations to and from other color space (i.e., CIELAB, and CIELUV) could account for white point changes and could provide device independence. Using these color spaces is more complicated. They require two transformations: one at the input device, and one at the output device.

2.5 Compatibility with Monochrome

Monochrome is the "lightness" or luminance of a color devoid of any chromaticity. For RGB and CMY luminance is spread across all three components. To convert RGB or CMY to monochrome all three components must be used. For YCrCb, CIEXYZ, CIELUV, and CIELAB, luminance is separate from chroma. For these color spaces converting to monochrome is straight-forward, since the luminance component is the monochrome version of the image.

2.6 Compatibility with Existing Standards

RGB (i.e., CIERGB), CIEXYZ, CIELUV, and CIELAB are international standards maintained by the Commission International de l'Éclairage (CIE) or International Commission on Illumination. All are derived from research done in 1931 that defined the RGB color space. These standards were developed with the premise that the stimulus for color is provided by the proper combination of a source of light, an object, and an observer. YCrCb is a digital television standard, CCIR 601.

2.7 Device Independence

A device independent color space allows an image to be obtained from dissimilar input devices and to be rendered on dissimilar output devices while maintaining a close or exact color match between resulting images. In general, this means that the device independent color space must account for changes in the white point. Of the color spaces reviewed, only CIELAB and CIELUV are white point independent.

2.8 Comparison

A comparison of the candidate color spaces shows CIELAB and CIELUV as being the best candidates for color facsimile. (See Table 2-1.) They have excellent color stability, excellent image quality, high compatibility with monochrome, are existing standards, and are device independent.

Table 2-1. Color Space Comparison

	RGB	CMY	YCrCb	CIEXYZ	CIELAB	CIELUV
Color stability	Poor	Poor	Poor	Poor	Excellent	Excellent
Image quality	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Color space transformations	Simple	Simple	Moderate	Moderate	Moderate	Moderate
Compatibility with monochrome	Low	Low	High	High	High	High
Compatibility with existing standards	Yes	Yes	Yes	Yes	Yes	Yes
Device independence	No	No	No	No	Yes	Yes

3.0 COMPRESSING COLOR

The Joint Photographic Experts Group (JPEG) has been working on a still image color compression standard since 1986.[11] This work has its roots in Working Group 8 (WG8) of ISO/IEC JTC1/SC2 (Coded Representation of Picture and Audio Information) which was set up in 1982. A CCITT special rapporteur's group was formed in 1986 by experts from both WG8 and New forms of Image Communication (NIC) with the expressed goal of selecting a high performance universal compression technique. Most of the technical work on JPEG has been completed, and has resulted in CCITT Recommendation T.81, "Digital Compression and Coding of Continuous-tone Still Images," and Draft ISO Standard (DIS) 10918-1, "Information Technology-Digital Compression and Coding of Continuous-tone Still Images-Part 1: Requirements and Guidelines."

The Joint Bi-level Image Group (JBIG) was formed in 1988 and organized much the same way as JPEG. JBIG can be thought of as a spin-off of JPEG, because the original goals of JPEG included compression of bi-level images. JPEG members were unable to produce an algorithm that worked well on both continuous-tone and bi-level images. As a result, it was decided that JPEG would concentrate on continuous-tone image compression, and JBIG would select and develop a compression technique for a general class of bi-level images. The precision of each is 5 to n and 1 to 4 bits/pixel/component respectively.[12] (See Figure 3-1.) Most of the technical work on JBIG has been completed and has resulted in CCITT Recommendation T.82, "Coded Representation of Picture and Audio Information-Progressive Bi-level Image Compression," and DIS 11544, "Information Technology-Coded Representation of Picture and Audio Information-Progressive Bi-level Image Compression."

An ad hoc group was created early in 1990 to address color facsimile under Question 4 of CCITT Study Group VIII. This group now considers JPEG to be the leading candidate for continuous-tone color facsimile compression.

Two types of color spaces have been discussed: "primary" color spaces such as RGB and CMY, and luminance-chrominance color spaces like CIEXYZ,

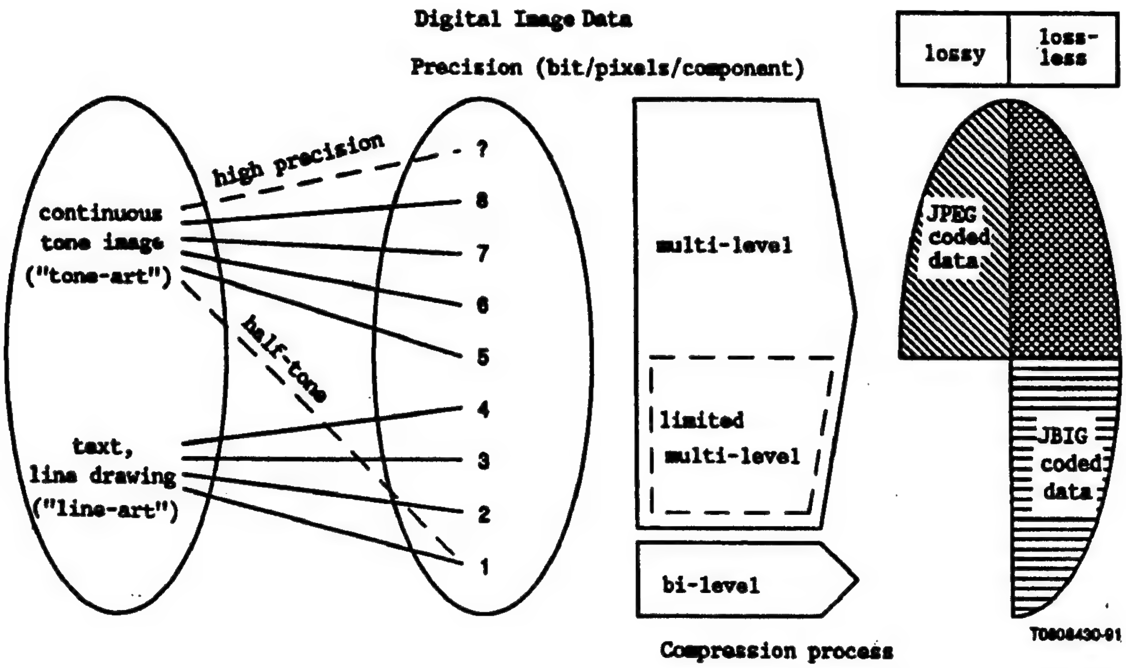

Figure 3-1. Typical Application Areas of JBIG and JPEG with Regard to Digital Quantization/Precision of Data

CIELAB, etc. The RGB and CMY spaces are naturally associated with scanners and printers, while the luminance-chrominance spaces offer gray-scale compatibility and probably higher compression. For the primary spaces, luminance is spread across all three components, whereas for the luminance-chrominance spaces it is not. In addition, since the eye is less sensitive to changes in chrominance than luminance, it is easier to optimize a compression technique for separate luminance and chrominance components. For the luminance-chrominance spaces, subsampling the chrominance components provides further compression. Much of the JPEG research has been based on the YCrCb color model. This research should apply equally well to other luminance-chrominance spaces.

3.1 JPEG

JPEG specifies two classes of coding processes, lossy and lossless processes.[13] The lossy processes are all based on the discrete cosine transform (DCT), and the lossless are based on a predictive technique. There are four modes of operation under which the various processes are defined: the sequential DCT-

based mode, the progressive DCT-based mode, the sequential lossless mode, and the hierarchical mode.

In the sequential DCT-based mode, 8x8 blocks of pixels are transformed, the resulting coefficients are quantized and then entropy coded (losslessy) by Huffman or arithmetic coding. The pixel blocks are typically formed by scanning the image (or component) from left to right, and then block row by block row from top to bottom. The allowed sample precisions are 8 and 12 bits per component sample. Of the DCT-based methods, the sequential DCT-based mode requires the least amount of storage.

For the progressive DCT-based mode, the quantized coefficients for the complete image component are determined, stored, and processed in one or both of two complementary ways, spectral selection, and successive approximation. In spectral selection, the coefficients are grouped into spatial frequency bands, and a group is typically sent for the whole image component. In successive approximation, the most significant bits of the coefficients are sent before the least significant bits. These two techniques may be used separately or may be combined in various ways.

The sequential lossless mode is not based on DCT at all, but is a totally independent predictive coding technique. The predicted value of each pixel position is calculated from the three nearest neighbors above and to the left, and the difference between the predicted value and the actual value is entropy encoded losslessly. For the lossless mode of operation, sample precisions from 2 bits per sample to 16 bits per sample are allowed.

In the hierarchical mode, an image component is transmitted with increasing spatial resolution between progressive stages. This is accomplished by first downsampling the image a number of times to produce a reference stage, which is transmitted by one of the other three modes of operation. The output of each hierarchical stage is used as the prediction for the next stage and the difference is coded. The coding of the differences may be done using only DCT-based processes, only lossless processes, or DCT-based processes with a final lossless process for each component.

All decoders that include any DCT-based mode of operation must provide a default decoding capability, referred to as the baseline sequential DCT process. This is a restricted form of the sequential DCT-based mode, using Huffman coding and 8 bits per sample precision for the source image.

3.2 JBIG

Like JPEG, the JBIG algorithm should be capable of providing progressive (multi-stage with improving quality) or sequential image build-up.[14] In addition, it should be image-preserving, such that the final decoded image is identical to the original.

The progressive bi-level coding technique consists of repeatedly reducing the resolution of a bi-level image, R_0, creating images R_1, R_2,..., R_n. Image R_i has half the number of pels per line and one-half the number of lines of image R_{i-1}. The lowest-resolution image, Rn, called the base layer, is transmitted losslessly by binary arithmetic coding. Next, image R_{n-1} is transmitted losslessly, using pels in R_n and previously-transmitted pels in R_{n-1} as predictors in an attempt to predict the next R_{n-i} pel to be transmitted. If prediction is possible (both transmitter and receiver are equipped with rules to tell if this is the case), the predicted pel value is not transmitted. This progressive build-up is repeated until image R_0 has been losslessly transmitted. A sequential mode of transmission also exists. It consists of performing the entire progressive transmission on successive horizontal stripes of the original image.

3.2.1 Applicability to Facsimile

The full JBIG algorithm is appropriate to data base storage, browsing and retrieval, with various resolutions from icons to full-scale images. If the full functionality were added to terminals that were intended to provide softcopy interactive capability, such as Group 4 Class 3, then users of such terminals would realize the full benefits of the progressive algorithm. For point-to-point facsimile transmission, as typified by Group 3 a single-layer subset of the full JBIG algorithm

might be more applicable. In this subset, it is likely that sequential transmission would be used.

In sequential transmissions, the number of layers and the number of lines per stripe are free parameters with a wide range of allowable values. If the number of layers were set to one and the number of lines per stripe set large enough to permit just one stripe, a "pure" sequential transmission would result. This limiting case might be applicable to low-cost facsimile implementations.

3.2.2 Resolution Reduction

The simplest method of reducing an image to half its size in both dimensions is straight subsampling: keep every other pel in a given high-resolution line, and do this to every other line. In bi-level images, however, this method quickly washes out detail. In images containing text or line drawings, lines forming the drawings or text characters grow thinner with each reduction, and soon disappear. In halftone images, gray levels become badly distorted. The resolution reduction algorithm for JBIG consists of two parts: a formula for determining a low-resolution pel value, and a list of exceptions that override the formula. The formula is in effect a filter, and the exceptions seek to preserve such features as lines, edges, and dither patterns.

The resolution reduction method has been found to achieve excellent results for dithered and halftoned grayscale. In general, it accepts a high-resolution image and creates a low-resolution image with, as nearly as possible, half as may rows and half as many columns as the original. The algorithm is identical for all resolution layers.

The high-resolution image is divided up into two by two blocks of pixels, and each of these superpixels is mapped to one low-resolution pixel in the reduced-resolution image. The low-resolution pixels are determined from left to right and from top to bottom. The color of a low-resolution pixel is determined from the high-resolution pixels in the superpixel, neighboring low-resolution pixels, and neighboring high-resolution pixels. (See Figure 3-2.)

This mechanism is geared towards resolution reductions that are a power of two. For other reductions a different mechanism is necessary. In general, specific resolution reductions can be viewed as slices out of a continuous resolution reduction space. Within that space certain image features are preserved (lines, edges, etc.).

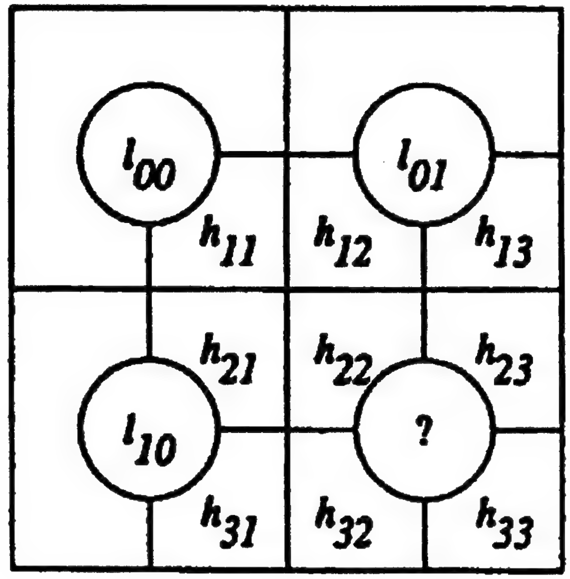

Figure 3-2. Pixels Used to Determine Color of a Low resolution Pixel

3.2.3 JBIG and Color

In JBIG each pixel in a plane is either 0 or 1. When the image is bi-level, a 1 bit indicates the foreground color and the 0 bit indicates the background color. The mapping of intensity and color to more than one bit plane is not currently defined by JBIG. In one approach, 5 bits per pixel would be sufficient to convey a luminance-chrominance color space (e.g., CIELAB or CIELUV). One bit plane conveys the luminance component, and the remaining 4 bit planes convey the chrominance components (2 bits per component). If the chrominance components are stripped away, the resulting image is bi-level. At least two bits per chrominance component are needed to take advantage of the opponent-style nature of the color spaces. For example, for LUV, the u can be considered to be red-neutral-green, and v can be considered yellow-neutral-blue.

3.2.4 Continuous Resolution Reduction

JPEG and JBIG permit certain fixed resolution reductions. For JPEG they are 2:1, 3:1, and 4:1; for JBIG they are powers of 2. Facsimile equipments use a variety of resolutions, and some conversions may fall outside this set (e.g., 300 to

240, 300 to 200, etc.). To ease resolution reductions between facsimile equipments and with other devices, a general purpose algorithm may be applicable.

Specific resolution reductions are, in effect, slices out of a continuous scale of theoretical image resolutions. (See Figure 3-3.) Algorithms developed for specific reductions and tailored to specific image characteristics could be viewed as special cases of a as yet to be defined general reduction algorithm. The general algorithm would permit scaling to any size. To be successful this algorithm would have to be robust, simple to implement, and compatible with existing reduction algorithms.

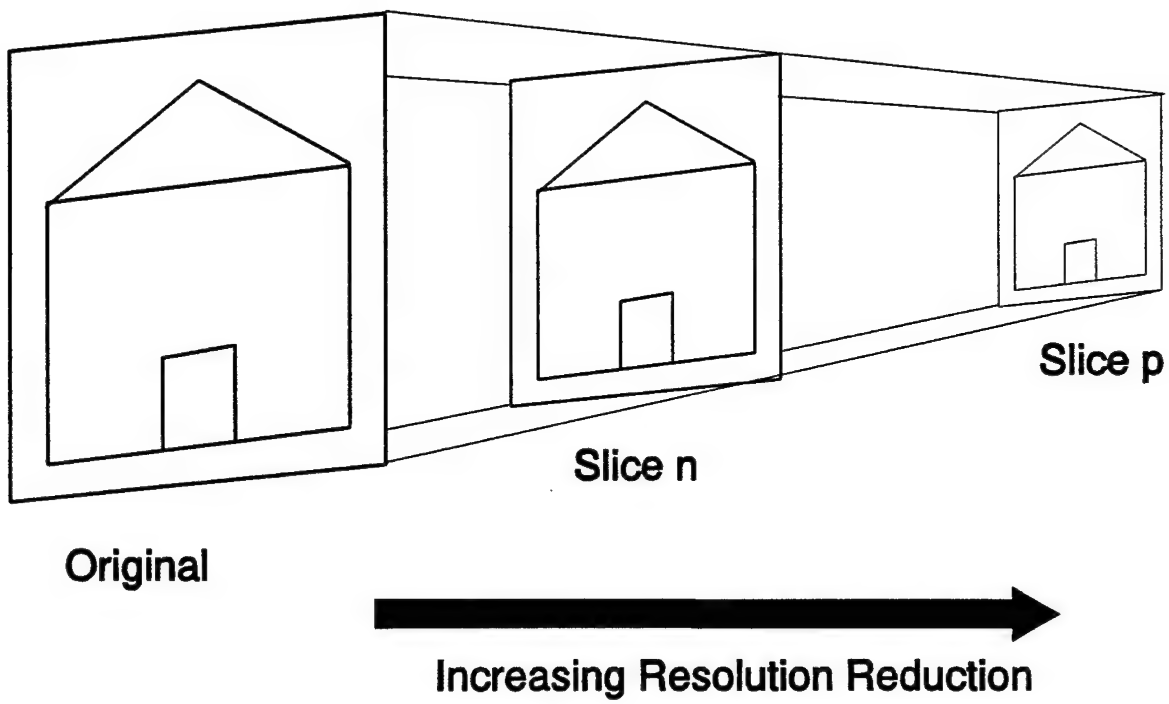

Figure 3-3. Continuous Resolution Reduction

Since the algorithm is being applied to a continuous resolution scale, and given the possible uncertainty about what features should be preserved at points on that scale, an algorithm should probably be selected that can account for both. One candidate is fuzzy logic. Fuzzy logic can often replace complex requirements and complex implementations with an amazingly simple and easily maintained implementation.[15],[16] Fuzzy logic is a method of easily representing analog

processes on a digital computer. These processes are usually concerned with continuous phenomena that are not easily broken down into discrete segments, and are difficult to model along mathematical or rule-based lines.

The components of conventional and fuzzy systems are similar. They differ mainly in that fuzzy systems contain "fuzzifiers," that convert inputs into their fuzzy representations, and "defuzzifiers," that convert the output of the fuzzy process into "crisp" solutions (e.g., 1's and 0's for bi-level imagery).

A fuzzy system permits subjectivity to play a role. Rules can be written in terms of imprecise ideas of what constitutes the states of the variable. For example, one rule might be

☞ if a halftone pattern is **present** preserve the halftone pattern within it's reduced spatial area.

A rule in a conventional system would need to be very specific:

☞ if pixel 1 is black, 2 is white, etc., preserve the pattern as ... in it's reduced spatial area.

With careful design a fuzzy algorithm could preserve edges, halftone and dither patterns, etc., while providing a robust resolution reduction capability.

4.0 ENHANCING GROUP 3 AND GROUP 4 FACSIMILE TO INCLUDE COLOR

Modifications can be made to Group 3 and Group 4 facsimile Recommendations to include color. For Group 3, these modifications could be limited to the DIS/DCS. For Group 4, the raster graphics content architecture and document application profile would be modified. Examples of bits that must be defined are JBIG coding, JPEG coding, color space, interleave format, bits/color space component, spatial resolution of each color space component, and build-up.

JBIG and JPEG coding probably will be used for "bi-level" and continuous-tone color coding, respectively. (Bi-level color is where each color (e.g., RGB) is either on or off.)

For Group 3, if both transmitting and receiving terminals have the same capability, then they can use that coding mechanism instead of T.4. (This would also be true for Group 4 and T.6.) One required condition for Group 3 is the error correction mode. Like T.6, JBIG and JPEG have no built-in mechanisms to limit the effects of transmission errors. (T.6 in Group 3 requires the use of the error correction mode to ensure error-free transmissions.) As a result, error correction mode is mandatory to ensure JBIG and JPEG transmissions are error-free. Group 4 on the other hand has no such requirement; it assumes error-free transmissions.

In general, the modifications must specify the parameters needed to use JPEG and JBIG in conjunction with color. (JPEG and JBIG can be viewed as toolkits, where the user decides how they will be used.) Additional specifications are needed for JBIG, however, to specify how color is mapped onto JBIG bit planes. If a luminance-chrominance color space is used, the luminance component (bi-level) could be mapped onto the least significant bit plane. The chrominance components (if 2 bits each) could be mapped onto the four most significant bit planes. At least two bits per chrominance component are needed if an opponent-style color space is used. Similar specifications are necessary for JPEG.

Compatibility with existing facsimile standards is highly desirable, and includes the ability to send a color space's luminance component only to existing

terminals. An appropriate color space to use is probably CIELAB. It is device independent and is designed for print.

4.1 CCITT Study Group VIII Efforts

CCITT Study Group VIII is currently studying adding color to facsimile, in particular Group 4.[17],[18] Their discussions include deciding upon a color space, a color component interleave, subsampling, and normalization tables.

CIELAB is favored by several members of the Study Group. It explicitly includes white point normalization. It can reference the XYZ space directly and can, therefore, represent any point in the XYZ space. CMY(K) is being considered as an optional space. It is device dependent, so a standard implementation should be used. CMY(K) might allow simple, low-cost printers and receivers for server systems by putting all color calibration at the transmitter or server. It also allows for direct use of CMY(K) devices that currently exist and that have no color calibration capability on board.

Block interleave is being proposed as mandatory to provide compatibility with the JPEG standard and to allow for reduced memory requirements. Pixel, line, and component interleave are being considered as options. Pixel and line interleave are alternate forms of block interleave, but they can simplify receiver processing in some applications. Component interleave is an important option for CMY(K) devices that print full pages of each component in sequence. Without this option, images will either have to be transmitted more than once, or full page memories will be required.

The output quality of conventional digital hardcopy devices is often worse than for devices like monitors. This is usually due to required halftoning in inexpensive devices. As a result, one proposal that Study Group VIII is assessing is that Group 4 include the nine combinations of horizontal and vertical subsampling factors (i.e., 2:1, 3:1, and 4:1) for each color independently, as required by JPEG. This also includes allowing custom subsampling patterns.

Since text, halftones, and continuous-tone color images have different optimal JPEG encoding and normalization tables, one proposal recommends that custom tables be permitted for each color component, as required by JPEG. Default tables could be provided subject to determining appropriate values. Note that the tables designed for the JPEG standard did not include scanned text or halftones. JPEG coding of these images are likely to be suboptimal in systems where these are the common image type.

5.0 REGENERATING IMAGES FROM HALFTONES

Halftones when scanned and converted to bi-level images usually have moire patterns that are a result of the scanning, conversion and printing process. Scanning and printing at high enough rates (typically >1200 dpi) to eliminate moire patterns is usually impractical.[19] By reconstructing a grayscale from a halftone, filtering the grayscale, and generating a new halftone, it may be possible to reduce distortions.

Halftones usually consist of a repetitive dot pattern where the size of the individual dots determine the perceived grayscale. (The human eye integrates these dots over a given area.) For halftones, the primary artifact generated is the high frequency dot pattern. At normal viewing distances, a dot frequency of 100 cells/inch or higher results in a relatively invisible artifact to the human eye and requires at a minimum a 400 pixel/inch printer. (A cell is the permitted area in which a halftone dot may grow; see Figure 5-1. The smallest possible dot could be called the halftone pixel.) Below 85 cells/inch, the cell, false contours, and textural contours become visible.

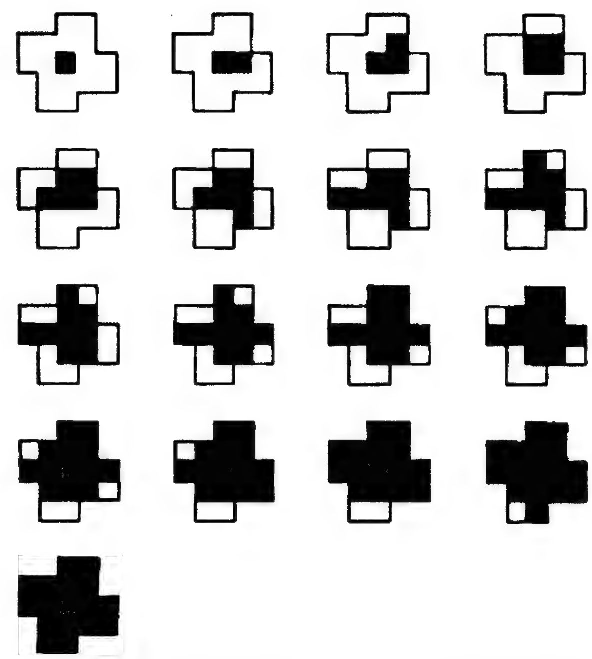

Figure 5-1. Halftone Representation Using Pixels

Most PC and facsimile scanners typically scan at 200 to 300 pixels/inch.[20] As a result they are usually unable to sample at a high enough rate to distinguish individual halftone cell sizes. (i.e., sampling at more than twice the resolution of a halftone pixel.) When this is the case, scanners tend to sense

halftone cells as "grayscales." In addition, the resolution is reduced from that of the halftone pixel to the resolving power of the scanner. That is, the scanner pixel may encompass more than one halftone pixel and possibly more than one halftone cell. In effect, these scanners are performing a resolution reduction (from that of the halftone pixel to that of the scanner pixel) and grayscale conversion simultaneously. By taking advantage of the grayscale information, it may be possible to enhance the image quality of resulting bi-level images, and may result in better image quality than provided by traditional conversion techniques (dithering, etc.).

A filter applied to the image might seek to enhance edges, lines, periodic patterns, and dither patterns by taking advantage of the different grayscale levels sensed. This filter could be modeled on JBIG's resolution reduction algorithm. It could also do filtering and bi-level thresholding in one pass.

Pixels that must be judged either white or black are the scanned pixels with gray levels between pure white and pure black. These "grayscale" pixels and the already judged pixels could be used to determine the bi-level color of up and coming grayscale pixels. This filter, like JBIG's, might consist of a formula for determining a pixel value, and a list of exceptions that override the formula. The exceptions would seek to preserve edges, lines, and periodic and dither patterns.

Figure 5-2 shows the scanned grayscale and bi-level pixels that could be used to determine the color of a bi-level pixel, denoted by "?". Its color is determined not only by the corresponding grayscale pixel, but by eight peripheral grayscale pixels and four previously determined bi-level pixels.

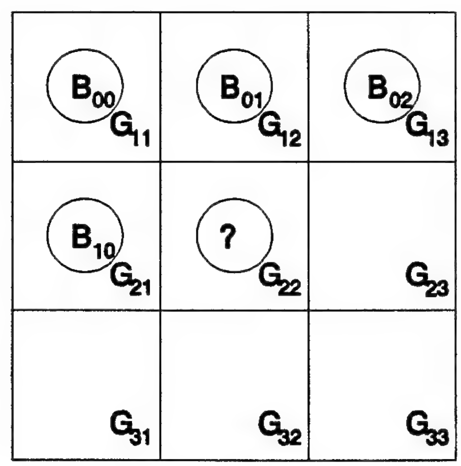

Figure 5-2. Pixels used for Filtering

6.0 CONCLUSIONS, RECOMMENDATIONS, AND ITEMS FOR FUTURE STUDY

An appropriate color space for facsimile that provides compatibility with other color spaces is either CIELAB or CIELUV. Both can account for the different white points of input devices (e.g., cameras, scanners), softcopy output devices (monitors), and hardcopy output devices (printers). CIELAB is preferred because it is designed for printed material.

The inclusion of color into Group 3 and Group 4 facsimile standards should probably take advantage of the JBIG and JPEG coding algorithms; where JBIG is used for "bi-level" color imagery, and JPEG is used for continuous-tone color imagery. For both Group 3 and Group 4, the modifications might include JBIG or JPEG coding, color space (default: CIELAB; others optional), interleave format (default: block), bits/color space component (default: JBIG - 1:2:2 (LAB); JPEG - 8:8:8), and spatial resolution of each color space component (default: resolution times 1:½:½). For Group 3 most of the modifications would occur in the DIS/DCS, and the transmitting and receiving terminals would negotiate capabilities. For Group 4, most of the modifications would occur in the raster graphics content architecture and document application profile.

The regeneration of an image from a halftone is very dependent on resolving power of the scanning process. If the scanner is unable to scan a document at a sufficiently high rate, the scanner is performing, in effect, a resolution reduction. A filter could be applied that takes advantage of the sensed gray levels and seeks to preserve edges, lines, periodic patterns, and dither patterns.

Items for future study might include

- Analyzing the compressibility of RGB, CMY, and CIELAB components using JPEG and JBIG with varying component spatial resolutions, and the resulting image quality.

- Implementing and analyzing a filter for regenerating images from halftones.

- Implementing and analyzing a continuous resolution reduction algorithm based upon fuzzy logic.

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